UNIT TWO

3 PARTICLE DETECTORS

Introduction

In this chapter we shall discuss nuclear radiation detectors and counters. The radiation could be charged particles, photons and neutrons. The interaction of any type of radiation always involves charged particles at some stage in the process. For uncharged radiations such as γ-rays and neutrons there is transfer of some of the energy to charged particles before there is any effect on the absorbing medium.

Nuclear detectors

The evolution of the techniques of nuclear radiation detection has played a vital role in unraveling the mysteries of the atomic nucleus. The radiations coming out of the nucleus such as the α, β and γ rays are the signals which carry with them information about the properties of the nucleus. Hence their detection and measurement are of prime importance in understanding the structure of the nucleus.

The principle of nuclear radiation detection can be broadly divided into three classes.

(a) Methods based on the detection of free charge carriers: During the passage of an ionizing radiation through a medium (solid, liquid or gas) both positive and negative ions are produced. Since ionizing radiation comprises charged particles moving with high velocity, the method is primarily applicable in the case of charged particle detection. Uncharged radiation like gamma rays or neutrons can also be detected by instruments based on this method since they usually eject charged particles which then cause ionization in the medium.

Instruments based on this method include ionisation chambers, proportional counters, Geiger-Muller counters and semi- conductor detectors.

(b) Methods based on light sensing: These are also applicable for both charged particle detection and detection of uncharged radiation.

Instruments based on this method include scintillation counters and Cerenkov detectors.

(c) Methods based on the visualization of the tracks of the radiation:

These are applicable for the detection of charged particles and include instruments like the Wilson cloud chamber, bubble chamber, nuclear emulsion plates, spark chamber and solid state track detectors.

Hybrid detectors combining both ionization method and light sensing method have been used for special purposes.

Methods for the detection of free charged carriers

When an energetic heavy charged particle moves through a substance, it loses energy by repeated ionising collisions with the atomic electrons in the substance. In each collision, a pair of positive and negative ions is produced. The negative ions are usually electrons. In the case of a solid medium, instead of a positive ion, a positively charged hole is created. The positive and negative ions including the positive holes are the charge carriers. This ionisation process is known as primary ionisation. The positive and negative electrodes placed within a detector attract the oppositely charged ions produced in the medium between them which gives rise to an ionisation current. This can be recorded by a suitable measuring device to record the event (i.e., the passage of the particle through the medium) while moving towards the electrodes, the ions suffer repeated collisions with the atoms in the medium. If the potential difference between the electrodes in the detector is sufficiently high, then the primary ions produced in the medium may gain an amount of energy high enough to produce another ion pair which will also move towards the opposite electrodes. These in turn may produce further ionisation by collision. All the secondary ions thus produced add up with the primary ions and thus an amplified current is recorded by the detector. This process is known as gas amplification. Ionisation champers, proportional counters, Geiger Muller counters and semiconductors are based on this method, which we are supposed to study.

Wilson cloud chamber

It is an instrument used for the visual observation of the tracks of the charged particles in their passage through matter. C.T.R. Wilson was the person who first designed this and hence called Wilson cloud chamber.

Principle

When air mixed with saturated water vapour is suddenly expanded (adiabatic), it will result in fall of temperature and super saturation of vapour. The vapour will condense in cloud of water droplets. The production of such a cloud is however impossible unless nuclei on which the water vapour may condense are provided. If particles of dust are present in the air they will act as condensation nuclei. But in dust free air this phenomenon of condensation and formation of cloud will not occur. C.T.R Wilson discovered that the condensation cloud could be produced even in dust free air provided the air was ionised by an ionising agent such as X-rays, cathode rays or any other nuclear radiations. When ionising agent entered the chamber immediately before or after the expansion, the ions left in its path would act as a condensation nuclei.

The experiment shows that as super saturation increases, the negative ions first serve as centres of condensation, then as the volume increases both positive and negative ions serve as the nuclei of droplets.

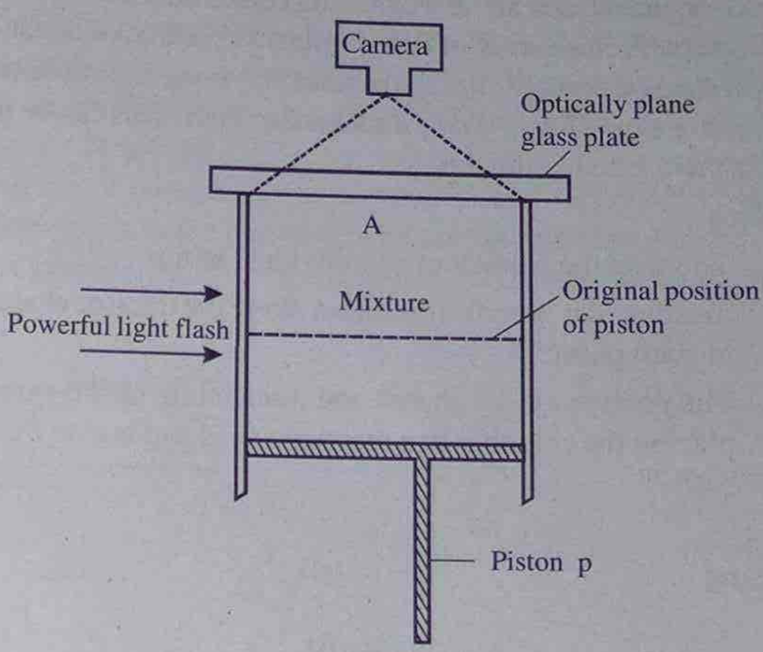

Figure 3.1

In short the working principle of cloud chamber is that charged ions can serve as nuclei of condensation of water droplets in a dust free atmosphere of air-water vapour mixture under the conditions of supersaturation.

Construction

Wilson cloud chamber consists of a large air tight cylindrical chamber A with the walls and ceilings are made of glass. The chamber contains dust free air saturated with water vapour or some other volatile liquid. The mixture inside the chamber can be compressed or expanded with the help of a piston p. The surface of the piston is usually covered with black felt so that no light is reflected from it to enter into the camera facing the front side of the chamber.

Working

To begin with the piston p is moved suddenly down. As a result of this the mixture undergoes adiabatic expansion due to which temperature falls. At this reduced temperature the mixture becomes supersaturated with the vapour and remains as such without any condensation of the vapour. For condensation to occur nuclei centres are required. For this a power full light flash is allowed to pass through the mixture immediately before or after moving the piston. This results in ionisation. The positive and negative ions act as centres of condensation i.e., the ions act as the nuclei of droplets. A close array of fine droplets i.e., a kind of linear cloud called a cloud track will thus be formed. By using suitable strong illumination from the side, the track appears as a white line on a dark background. This can be photographed by means of a camera fitted at the top.

Uses

1. To study the behaviour of individual atoms
2. To study the specific ionisation along the track of charged particles and the range of such particles.
3. The polarity of the charge and momentum of the particle can be determined by placing the chamber in a magnetic field and noting the radius of curvature of the path.

Using $$\frac{mv^2}{r} = qvB$$

or $$mv = qBr$$

Note

1. The main disadvantage of the cloud chamber is that it needs a definite time to recover after an expansion. Hence it is not possible to have a continuous record of events taking place in the chamber.
2. It cannot be used for detecting high energy particles since the interaction of energetic particles cannot be completely observed in the chamber.

Bubble chamber

It is a high energetic particle detector discovered by D.A. Glaser at the University of Michigan in 1952.

Principle

We know that normally the liquid boils with the evolution of bubbles of vapour at the boiling point. If the liquid is heated under a high pressure, its boiling point is raised, above the normal boiling point, without boiling taking place. A sudden release of pressure will leave the liquid in a superheated state and the liquid does not boil immediately but remains quite for some time. If a ionising particle is incident on the liquid just after releasing the pressure, the ions left in the track of a particle act as condensation centres for the formation of bubbles. This is the principle on which bubble chamber works.

Construction

It consists of a cylindrical chamber containing liquid. To super heat the liquid a mechanism, with bellows and expansion piston, is fitted with the cylinder. The top and bottom of the cylinder are provided with optically plane glass plates. The whole system is enclosed in a temperature control. Light from a flash lamp enters the cylinder through the glass at the bottom of the cylinder. A camera is fitted at the top of the cylinder to take inside photograph of the cylinder. The bubble chamber is used in conjunction with electromagnet for determining the sign of the charge and momenta of the particles.

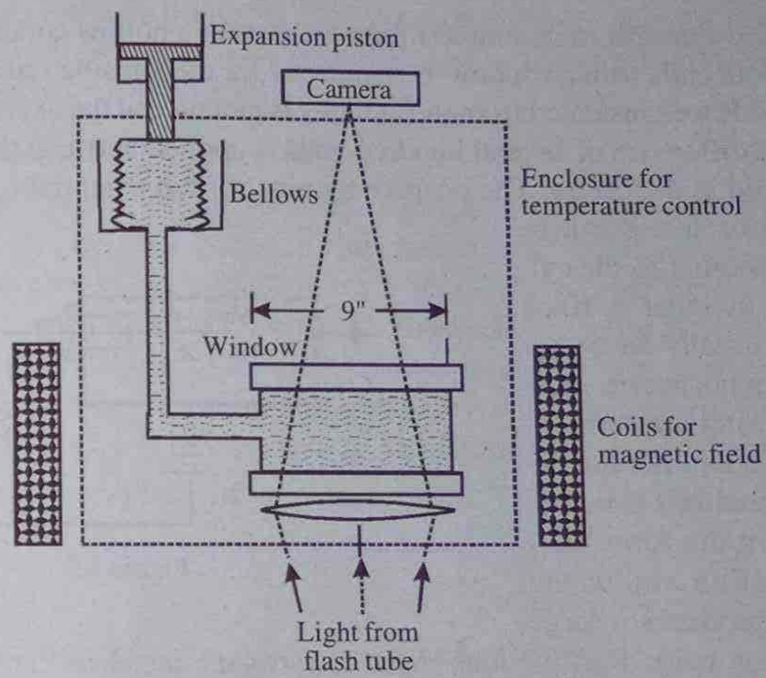

Figure 3.2

Working

The operating cycle of the bubble chamber consists of four stages.

1. The liquid is first heated to a temperature above its boiling point.
2. It is kept in the liquid state by the application of a pressure greater than its saturation vapour pressure.
3. The pressure is suddenly released so that the liquid becomes superheated and the flash lamp is switched on just before the pressure falls to minimum.
4. The grow of the bubbles occur for about milliseconds and the centres for the bubble formation last for about the same time.

A powerful lamp is then switched on within a millisecond to photograph the tracks. The cycle is then repeated.

Note : Various liquids have been used in the bubble chamber. Glaser used ethyl ether, later liquid hydrogen, deuterium and helium have been used. These have the advantage of having simple nuclei but the difficulty lies in their boiling points being very low. Thus the hydrogen chamber must be operated at about 26K. Heavy liquids such as pentane, propane and xenon have also been used.

Ionisation chamber

Ionisation chamber in its simplest form consists of a hollow conducting cylinder closed at both ends with a window W at one end for the ionising radiations to enter. A metal rod R well insulated from the cylinder is mounted at the axis of the cylinder. A potential difference of several hundred volts is applied between the cylinder and the metal rod at the centre. The positive terminal of the potential to the metal rod through a resistance R and the negative potential to the cylinder. The cylinder is filled with a gas usually air or hydrogen at atmospheric pressure or at greater pressures for γ – ray detection. For the detection of neutrons boron is introduced in the form BF_3. When radiation enters the chamber it produces a large number of ion pairs. Positive ions move towards the metal rod at the centre and negative ions towards the metallic cylinder. In order to count particles the pulses of current produced are fed to an amplifier.

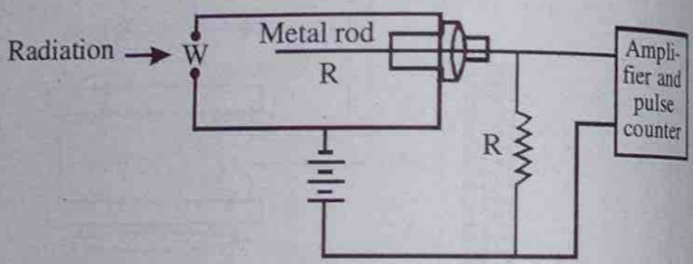

Figure 3.3

Proportional counter

When particles of low specific ionisation passes through an ionisation chamber, the pulses produced is too small to detect. One way of amplifying the signal obtained from a gas- filled detector is to increase the electric field so that the electrons gain enough energy between collision with gas atoms to cause further ionisation. In such a case the electrons produce further ionisation, and a rapid amplification of the original cascade occurs in what is called as Townsend avalanche. It should be noted that the size of the output signal is proportional to the number of ions formed by the primary ionisation process. Such a chamber is called a proportional counter.

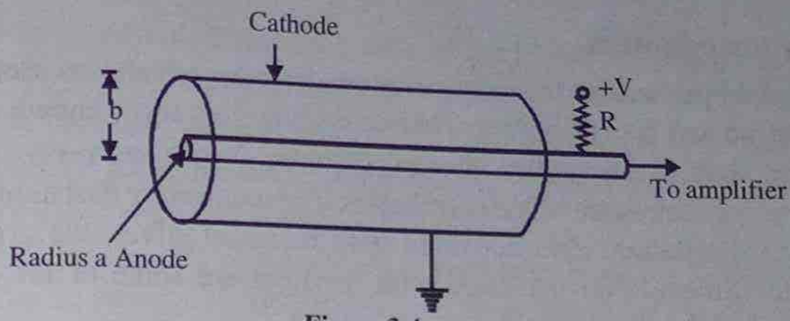

Figure 3.4

The proportional counter consists of a cylindrical gas filled tube (radius b Fig.) with a very thin central wire (radius a) which is insulated from the tube. The central wire is positive with respect to the tube which serves as the collecting electrode. This is connected to a pulse amplifier.

Geiger-Muller counter

Geiger-Muller Counter (G.M. counter) is in effect an improvement from the ionisation chamber. The principle of this instrument is the fact that the ions created by the entry of an elementary particle move in an intense electric field with such a high speed that ionisation by collision results. This causes a pulse of current which is used to record the incidence of the ionising particle. In G.M. counters this pulse is independent of the number of ions produced initially, while in proportional counter, the amplitude of the pulse is proportional to number of ions produced initially.

A G. M tube can be built in different geometries. Two most common forms are shown in Fig. (a) and (b)

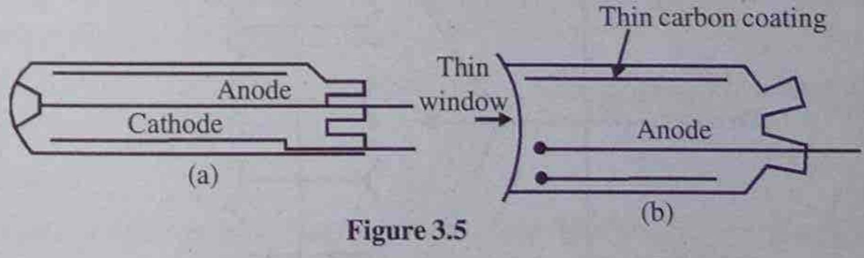

Figure 3.5

The first of these Fig (a) consists of a cylindrical copper cathode and a thin axial tungsten wire anode supported inside a cylindrical glass envelop. The ionising particle enters the counter through its glass walls. The second type Fig (b) is an end window counter. This modification is useful for less penetrating particles. The window is generally made of thin mica sheets. The anode is a tungsten wire and the cathode is in the form of a graphite coating.

Scintillation counters

This one of the earliest forms of radiation detectors which was used extensively by Rutherford and his colleagues. There are some substances known as phosphors which emit light flashes when charged particles, X-rays or γ-rays pass through them. These substances are called scintillators. The momentary flashes of light emitted are called scintillation. ZnS activated with traces of silver, the organic crystal anthracene stilbene, NaI activated with thallium are some of the examples of phosphors.

In older days the visible scintillations produced by the incident radiation were observed and counted through a microscope fitted with a screen coated with phosphor. This method of counting was very painstaking and required a period of adaptation of the eye within a dark room. ZnS was the phosphor used by Rutherford for the detection and counting of alpha particles.

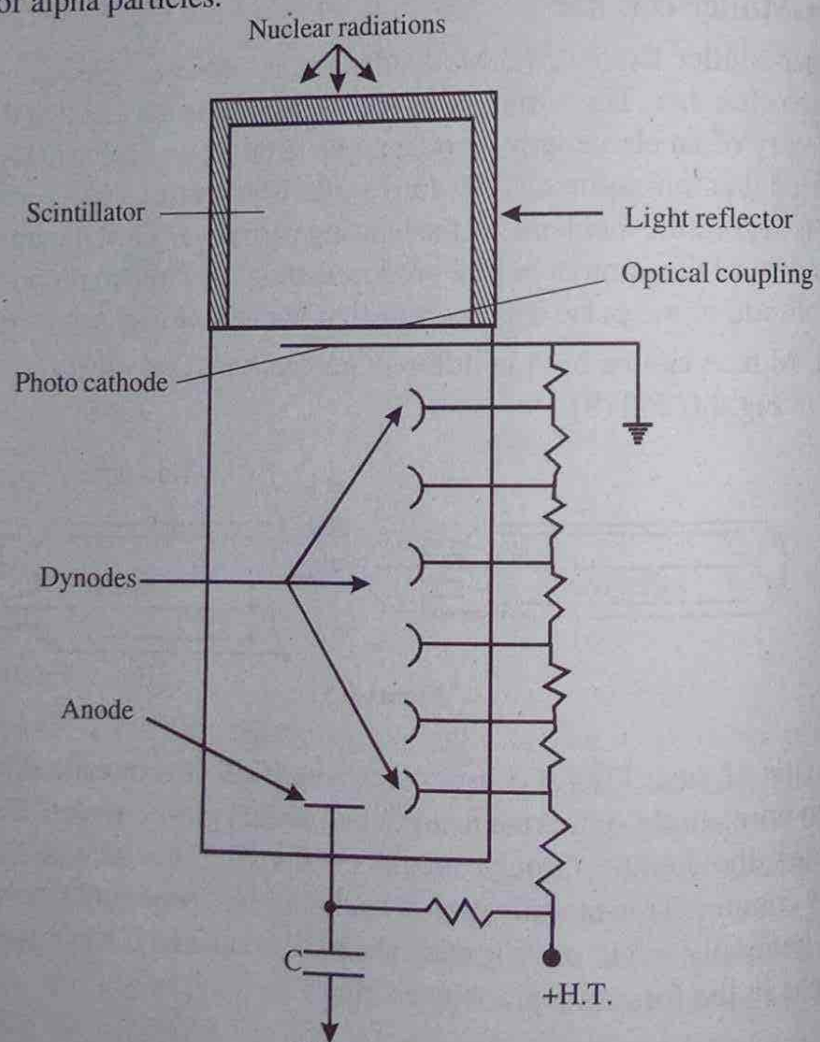

Figure 3.6

Nowadays very high speed electronic devices have been developed for detecting the scintillations taking place in times of the order of nano-seconds. Besides the detection of charged particles like α or β rays, high speed protons, deutrons can also be detected by the scintillation counters. This method has been found to be specially useful for γ -ray detection with high efficiency.

A schematic diagram of modern scintillation counter is shown below. A nuclear radiation falling on the scintillator can dissipate all its energy in it if the dimensions of the scintillator are large compared to its range. The scintillator produces scintillations (light pulses) which reach the photo cathode of a photo multiplier tube which is optically coupled to the scintillator. The photo multiplier tube consists of a photo cathode and several dynodes maintained at successively higher potentials of about 100 volts per dynode stage. When light pulses reach on photo cathode emit photoelectrons. A photo electron emitted by the photocathode is accelerated by the electric field to the first dynode where it produces a bunch of secondary electrons. These electrons are accelerated to the second dynode and produce more electrons. This process is repeated at each dynode. There are usually ten or more dynodes which ultimately achieve a gain of 10^7 to 10^8 by the time the electrons reach the last stage called the anode.

The magnitude of the output pulse from the photomultiplier is proportional to the energy of the particles incident upon the phoshor in a given scintillation counter. These pulses are fed to a pulse amplifier followed by a scaler circuit.

Advantages

1. It has a much higher counting efficiency for gamma rays due to the greater amount of energy dissipation by gamma rays.
2. It offers greater stability, greater accuracy, shorter resolving time and higher efficiency than G.M. counters.

Applications

1. Scintillation counters can be used to measure the particle energy.
2. Because of their rapid response they are used for the accurate timing of nuclear particles moving with very high speeds.
3. They are used to detect of antiprotons.
4. They are used in the study of cosmic rays, for the detection of mesons and other unstable particles of very high energy.

Semiconductor detectors

Semiconductor detectors are essentially reverse biased junction diodes. They have several advantages over other types of radiation detectors. They have better energy resolution, linear response over a wide range of energies of the incident radiation and fast time response.

A semiconductor detector consists of a semiconducting crystal sandwitched between two conducting electrodes. An electric field is applied across the electrodes. Passage of nuclear radiation produces hole-electron pairs which should move towards the appropriate electrode and the charge collected is used as a signal of the detection of radiation.

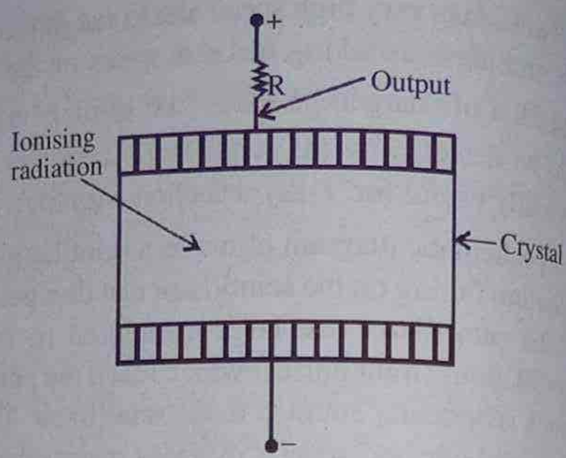

Figure 3.7

There are two types of semiconductor detectors:

(i) Diffusion junction detector

(ii) Surface barrier detector.

Diffusion junction detector

In a p-n junction diode, the electrons from the n-region and the holes from the p-region diffuse into the p and n regions respectively across the junction and form a double layer of charges, which prevents further diffusion and a self-adjusted potential barrier is created at the junction. If now the p-region is connected to the negative terminal of a battery and the n-region to the positively terminal, the arrangement is said to be reverse-biased (see Fig). As a result, the electrons and holes are drawn away from the junction region and a depletion layer is formed at the junction in which no charge-carriers are present (see Fig). Due to reverse bias, no current flows through the junction and the diode is cut off. The thickness of the depletion layer depends on the nature of the impurities and on the voltage applied. It usually lies in the range of several hundred microns to a few millimetres. Since the conductivity of the depletion layer is low, a large potential difference can be maintained across it. So it acts like an ionization chamber.

If now a high energy charged particle passes through the depletion layer, electron - hole pairs are generated. The electrons are raised to the conduction band and are free to move through the crystal under the action of the applied electric field. The holes left behind in the valence band also move freely through the crystal . Due to both these reasons, a momentary current impulse proportional to the number of elec-

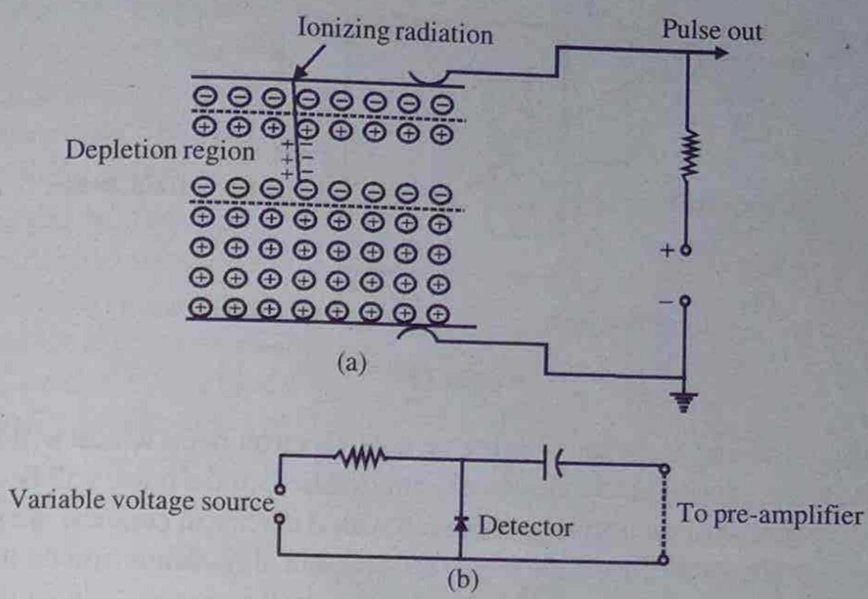

Figure 3.8

trons and holes is produced. Thus the semiconductor detector acts like a solid state ionization chamber. Since the energy needed to produce an electron-hole pair is only about 3 eV compared to about 30 eV required to produce an electron - ion pair in a gas ionization chamber, the registration of the electrical pulses in the semiconductor detector is easier and the accuracy of energy measurement much better (up to a fraction of a percent). In fact semiconductor detectors have the best energy resolution amongst all types of radiation detectors for most purposes. Because of the very narrow width of the depletion region, the pulse rise time is very small $(\sim 10^{-8}\,s)$ for these detectors.

Surface barrier detector

A very widely used surface barrier detector is the silicon surface barrier detector. A typical surface barrier detector is shown in figure.

It essentially consists of an extremely thin p-type produced on a high purity n-type silicon wafer. The combination constitutes a large area p-n junction diode. To construct the detector an n-type silicon wafer is taken and one of its surfaces is etched with acid and exposed to the air.

An oxidation layer is formed on the etched surface and this layer acts like a very thin p-type. Under the influence of an externally applied field electrons will be swept toward right and the holes to the left. As a result, an intermediate volume around the interface will be cleared of carriers of both signs and a depletion layer will be formed.

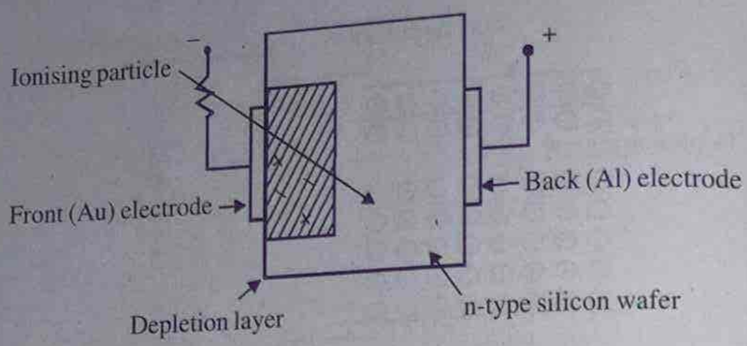

Figure 3.9

Passage of an ionising radiation will create hole-electron pairs which will be swept towards the appropriated electrodes by the applied field and a pulse will be obtained to signal the passage of the ionising radiation. Good electrical contacts are provided by evaporated thin gold film on the p-surface and thin aluminium film on the n-type silicon layer. These detectors have long stability, small size, negligible window absorption and linear pulse response over a wide range.

Spark chamber

This chamber is used in the field of high energy physics. It consists of a series of large parallel metal plates, several square feet in area, set in a chamber filled with neon gas at atmospheric pressure. All the plates are isolated from each other but alternate ones are grounded and the others are connected together to a high voltage d.c pulse generator (~ 15kV) which gives them high potential in short bursts of the order of a microsecond each. This is just enough to cause sparks to occur between the plates in such regions as are ionised by a particle entering the chamber. This gives a trail of sparks along the path of the particle which can then be photographed from the side.

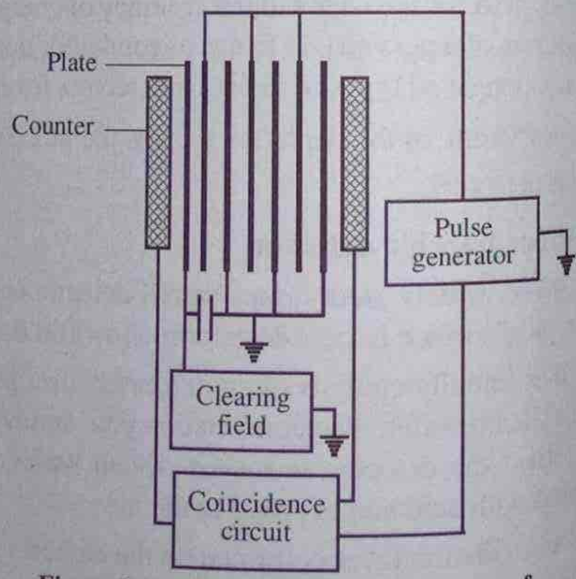

Figure 3.10: Schematic representation of spark-chamber circuit

Usually the plate separation is a few millimetres, a hundred or so, these plates can make a volume of some several cubic feet. the schematic representation of the spark chamber is given in figure below.

One of the main advantages of the spark chamber over the bubble chamber is that triggering and removal of ions by the clearing field are comparatively simple. But the origin of an event can only be found within an accuracy of one plate thickness. Faster timing is also possible.

With suitable counters at the end of the spark chamber, the particular event expected can be made to trigger the high voltage generator and so record itself. Thus a selection of events to be studied may be made.

A photograph of spark chamber tracks is shown in figure 3.11(a).

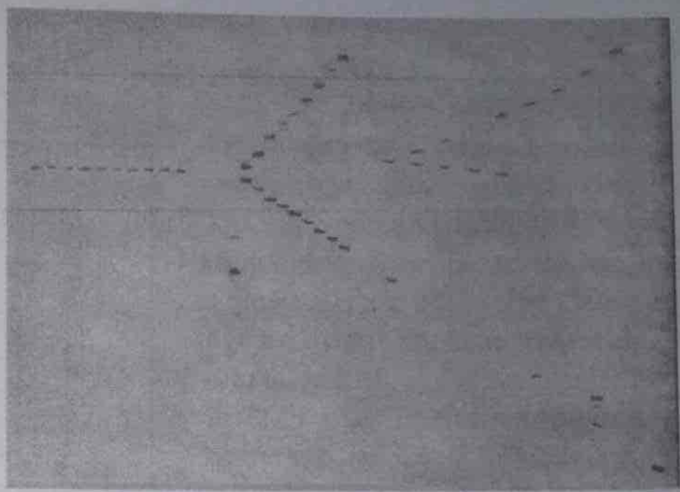

Figure 3.11: (a) Spark-chamber tracks

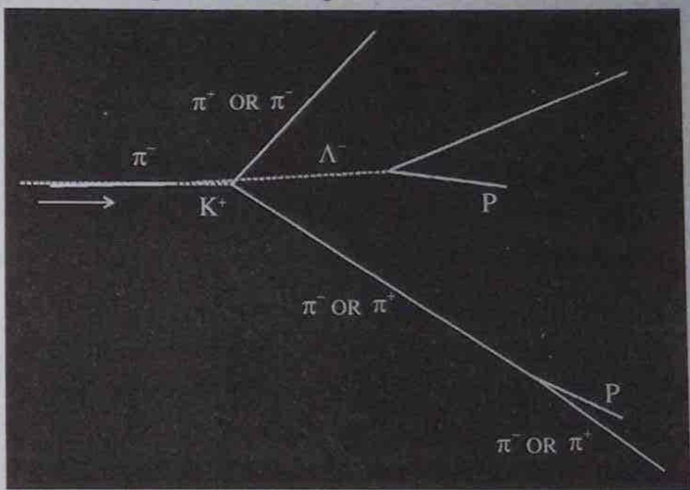

Figure 3.11: (b) Interpretation of tracks

Cerenkov counter

Cerenkov counters are particle detectors that make use of Cerenkov radiations.

When a charged particle passes through an optically transparent medium with a velocity greater than the phase velocity of light in that medium, it emits photons called Cerenkov radiation. The Cerenkov radiation is coherent at a particular direction (angle) relative to the direction of the particle.

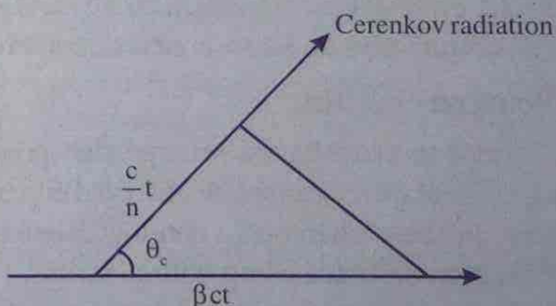

Figure 3.12

Particle velocity β

$$\therefore \qquad \cos\theta_c = \frac{c/nt}{\beta ct} = \frac{1}{\beta n}$$

The simplest Cerenkov counter consists of a barrel with enough volume containing distilled water to produced Cerenkov radiation. The outside of the barrel is silvered to make the inner side of the barrel reflective. This is to channel the light into a light gatherer. Just below it there is photon multiplier tube (PMT). PMT requires 1.5-2 kV for its operation. PMT is connected to a preamplifier. This is in turn connected to the output device. The schematic diagram of a Cerenkov counter is shown in figure 3.12.

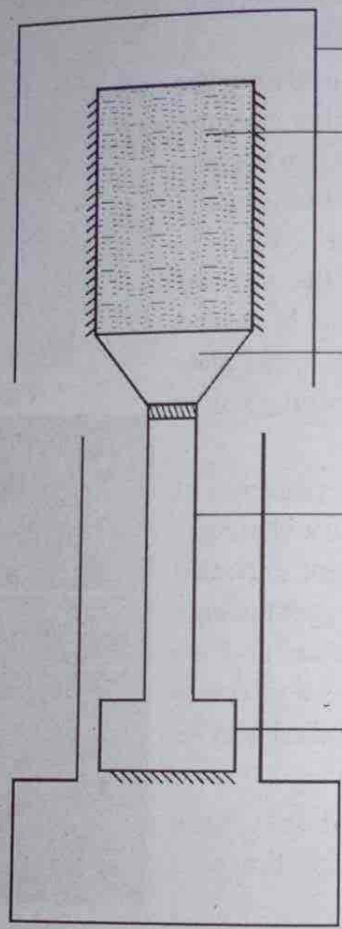

Figure 3.12: Cerenkov counter

Uses

1. It is used for prompt particle counting, the detection of fast particles, the measurement of particle masses etc.
2. It is used for tracking or localisation of events in very large natural radiators such as the atmosphere or natural ice fields like those of at the south pole in Antartica.
3. Used as detectors in, high energy physics, particle accelerators, nuclear reactors, cosmic rays and also in neutrino astronomy.

Neutron counting

Since neutrons have no charge, they produce no paths of ions as they move through a gas. Hence they cannot be observed either in cloud chambers or in ionisation chambers. In these chambers counting depends upon ionisation. So we have to create ionisation particles along with neutrons. For example, if boron is bombarded with neutrons, α-particles are produced:

$$^{10}_{5}B + ^{1}_{0}n \longrightarrow ^{4}_{2}He + ^{7}_{3}Li$$

Here each neutron produces an alpha particle $\left(^{4}_{2}He\right)$. This alpha particle will produce ionisation track which can then be used to identify the neutron. Thus for a counter to detect neutrons it must contain some gas which ionises after neutron collision with it molecules. This is possible with BF_3 gas in which boron atoms produce the α-particles which in turn produce ionisation which can be detected in the usual manner. Neutron counting chambers are either ionisation or proportional counting arrangements.

The photographic plate

In particle and nuclear physics, nuclear emulsion plate is a photographic plate with a particularly thick emulsion layer with a very uniform grain size. Like bubble chambers and cloud chambers etc. nuclear emulsion plate records the tracks of charged particles passed through it. they are very compact and produce cumulative record.

The plates are darkened by radiation from radioactive substances and the darkening is due to the production of individual tracks. The photograph given below shows various dark lines revealed by the silver grains. In order to record these successfully, specially prepared plates are used with emulsion thickness of hundred microns. Each type of particle has its own particular track. If neutrons are to be detected by this photographic plate, the plate must be socked in a boron solution.

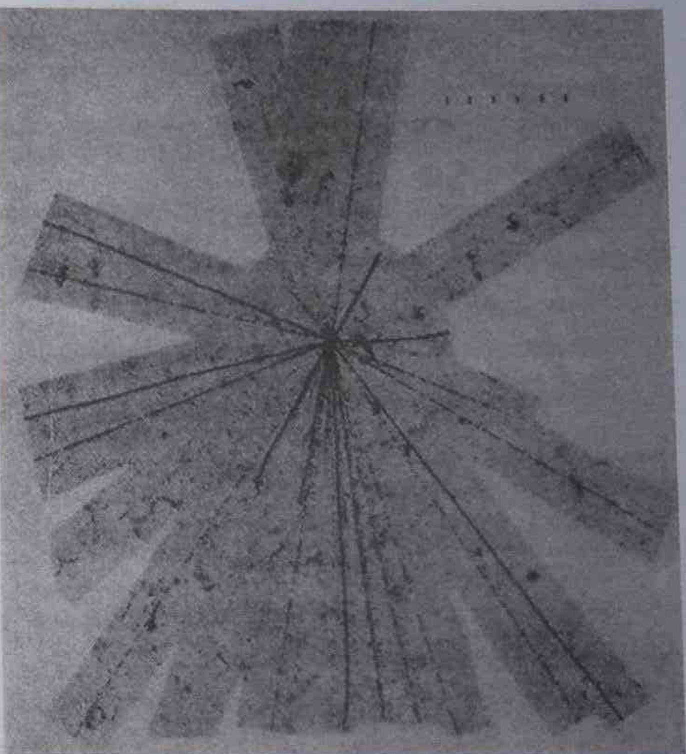

Figure 3.13: Disintegration of an emulsion nucleus by a high energy proton. The proton enters the plate top centre and produces a star by collision with a silver or bromine nucleus.

A disadvantage of the nuclear emulsion plate is that, unlike the cloud chamber tracks, nuclear plate tracks cannot satisfactorily be bent in a magnetic field since large amount of scattering obscures the curvature of the tracks which, in any, case are very short.

Nuclear emulsion plates are very compact and cheap. Thus for most of the works in nuclear physics they go for these plates.

UNIVERSITY MODEL QUESTIONS

Section A

(Answer questions in **two** *or* **three** *sentences)*

Short answer type questions

1. What is nuclear radiation detector?
2. What is a cloud chamber?
3. What is an ionisation chamber?
4. How will you measure the momentum of the charged particles by using cloud chamber?
5. What is the disadvantage of cloud chamber?
6. Mention three applications of cloud chamber.
7. What is a bubble chamber?
8. Draw the schematic diagram of a bubble chamber and label it.
9. What is the principle of ionisation chamber?
10. What is a proportional counter?
11. What is a Geiger-Muller counter?
12. Why the scintillation counters called so?
13. Give three applications of scintillation counter.
14. What are the advantages of scintillation counters?
15. Draw a schematic diagram of a scintillation counter and label it.
16. What is a semiconductor detector?
17. Draw the schematic diagram of a spark chamber and label it.
18. What is Cerenkov radiation?
19. What is a Cerenkov counter?
20. What is a nuclear emulsion plate?

Section B

(*Answer questions in a* **paragraph** *of about half a page to one page*)

Paragraph / Problem type questions

1. Classify the principles of nuclear radiation detection.
2. What is the working principle of a cloud chamber?
3. What is the principle of bubble chamber?
4. Briefly explain an ionisation chamber.
5. What is the principle of proportional counter?
6. Briefly explain a Geiger-Muller counter.
7. Briefly explain surface barrier detector.
8. Briefly explain the function of a spark chamber.
9. What is the principle of Cerenkov counter?
10. Explain briefly the working of Cerenkov counter.
11. Explain briefly the "neutron counting".
12. Give three uses of Cerenkov counter.

Section C

(*Answer questions in about* **two** *pages*)

Long answer type questions (Essays)

1. Discuss the principle, construction and working of an ionisation chamber.
2. Explain the principle, construction and working of Wilson cloud chamber.
3. Discuss the principle, construction and working of bubble chamber.
4. Explain the principle, construction and working of a scintillation counter.
5. Explain diffusion junction detector in detail.